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DIRECTORATE OF WEAPON RESEARCH (DEFENCE)

Joint Report by

The B.S.A. Group Research Centre and
The British Welding Research Association.

ON

WELDABILITY AND MECHANICAL PROPERTIES OF SOME LOW-ALLOY STEELS CONTAINING VANADIUM

Work carried out in connection with
Ministry of Supply Contract 6/Gen/ 1004

SEPTEMBER 1953

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THE MECHANICAL PROPERTIES AND WELDABILITY OF SOME LOW ALLOY STRUCTURAL STEELS CONTAINING VANADIUM

CONTENTS

FOREWORD

For some time the British Welding Research Association has been conducting on behalf of the Ministry of Supply an investigation having as its main objective the development of high tensile weldable structural steels.

The following reports in this series have already been issued:-

W.R.(D) 2/52 - "Correlation of Weldability Tests with Structural Joints"

W.R.(D) 2/53 - "Austenite Transformation Characteristics in Relation to Hard-Zone Cracking in Welded Low-Alloy Steels".

In the course of the research a large number of low alloy steels have been investigated and two in particular, known as steels A and B of the typical compositions given below, have been shown to combine good weldability with satisfactory mechanical properties in the normalised and normalised and tempered conditions.

	C	Mn	Si	S	P	Ni
Steel A	0.13/0.17	0.80/1.0	0.3 max.	0.035 max.	0.035 max.	0.5/0.7

Cr	Mo	
0.8/1.0	0.20/0.25	per cent.

	C	Mn	Si	S	P	Ni
Steel B	0.13/0.17	1.0/1.2	0.3 max.	0.035 max.	0.035 max.	0.2 max.

Cr	Mo	
0.5/0.7	0.20/0.25	per cent.

In the interests of providing alternative steels economising in molybdenum, the B.S.A. Group Research Centre suggested that this element could be effectively replaced wholly or in part by vanadium and with the agreement of the Ministry of Supply they prepared some experimental melts of vanadium bearing steels based on the composition of Steels A & B. In addition to preparing the alloys, the Research Centre also investigated mechanical properties and microstructures in the form of bar 1¼" dia. and place ⅝" thick, both in the normalised and tempered condition. The results of this work are given in Part I of the present report.

In order that the weldability of these alloys could be assessed in relation to the other experimental alloys previously examined by the B.W.R.A., plates ⅝" thick in each of the vanadium alloys were supplied to the B.W.R.A. by the B.S.A. Group Research Centre. The resulting tests by B.W.R.A. were described in B.W.R.A. Report M.O.S/L.21, which forms Part II of the present report.

Since the results described in Parts I and II applied to comparatively thin plates of the vanadium-bearing steels, it was thought desirable to carry out mechanical tests of the plates normalised so as to reproduce conditions equivalent to those resulting from treating thick plate. The results of these tests by B.W.R.A. were given in B.W.R.A. Report M.O.S/L.27, which is reproduced as Part III of this Report.

PART I

THE MECHANICAL PROPERTIES OF VANADIUM - BEARING HIGH TENSILE WELDABLE STEELS

By

The B.S.A. Group Research Centre, Sheffield

1. INTRODUCTION

The British Welding Research Association has carried out a considerable amount of research work in the development of high tensile weldable steels. As a result of this work, two steels have been selected which combine good weldability with satisfactory mechanical properties in the normalised and the normalised and tempered conditions, at the section sizes investigated. Both steels are alloyed with Mn, Ni, Cr and Mo; the actual chemical compositions are given in Table I below (Steels A and B).

In reaching these two steels, the effects of variations in Mn, Ni and Cr contents had been studied, but the Mo content had been maintained throughout at a constant value of 0.25%. It was suggested by the B.S.A. Group Research Centre that Mo could be effectively replaced by other alloying elements, notably V, and that the effects of this substitution should be studied in view of existing and possible future difficulties in the world supply of molybdenum. This suggestion was accepted and the B.S.A. Group Research Centre undertook to prepare suitable experimental melts of V-bearing steels, to investigate their mechanical properties and to supply material for weldability tests to be carried out by B.W.R.A.

This Report describes the preparation of the experimental steels, their heat treatment and their mechanical properties.

2. DETAILS OF EXPERIMENTAL WORK

(a) Specification and Actual Composition of Experimental Melts

The specification for the six experimental melts, 1 to 6, based on the two B.W.R.A. steels A and B, with the Mo content omitted or reduced, and with additions of V, as shown in Table I.

TABLE I

Specifications of Six Experimental Vanadium-Bearing Steels (Wt. per cent)

SPECIFICATION	C	Mn	Si	S	P	Ni	Cr	Mo	V
A	0.13 -0.17	0.80 -1.0	0.3 Max	0.035 Max	0.035 Max	0.5 -0.7	0.8 -1.0	0.20 -0.25	-
1	do.	do.	do.	do.	do.	do.	do.	-	0.15
2	do.	do.	do.	do.	do.	do.	do.	-	0.10
3	do.	do.	do.	do.	do.	do.	do.	0.10	0.10
B	do.	1.0 -1.2	do.	do.	do.	0.2 Max	0.5 -0.7	0.20 -0.25	-
1	do.	do.	do.	do.	do.	do.	do.	-	0.15
2	do.	do.	do.	do.	do.	do.	do.	-	0.10
3	do.	do.	do.	do.	do.	do.	do.	0.10	0.10

Three 20 lb. high frequency furnace melts were made to each of the six specifications, and a single 14 lb. ingot cast from each melt. The chemical compositions of the eighteen ingots are given in Table II.

TABLE II

Chemical Compositions of Steels Made to Specifications 1-6

CAST NO.	C	Mn.	Si	S	P	Ni	Cr	V	Mo	SPECIFICATION
3207	0.12	0.57	0.11	0.021	0.012	0.75	0.87	0.22	-	1
3208	0.17	0.69	0.11	0.021	0.010	0.70	0.90	0.22	-	1
3209	0.16	0.69	0.10	0.025	0.010	0.76	0.89	0.23	-	1
3210	0.15	0.78	0.09	0.025	0.010	0.73	0.92	0.14	-	2
3211	0.18	0.74	0.05	0.021	0.010	0.83	0.88	0.14	-	2
3212	0.19	0.90	0.05	0.021	0.011	0.83	0.90	0.12	-	2
3213	0.16	0.86	0.18	0.018	0.010	0.79	0.97	0.14	0.19	3
3214	0.17	0.99	0.20	0.021	0.010	0.78	0.95	0.14	0.19	3
3215	0.17	0.85	0.13	0.028	0.010	0.75	0.96	0.10	0.21	3
3216	0.20	1.24	0.16	0.025	0.010	0.10	0.71	0.23	-	4
3230	0.17	1.23	0.15	0.021	0.010	0.10	0.70	0.19	-	4
3231	0.16	1.13	0.15	0.020	0.010	0.08	0.68	0.20	-	4
3232	0.15	1.21	0.16	0.022	0.010	0.14	0.68	0.18	-	5
3233	0.13	1.13	0.14	0.024	0.011	0.12	0.69	0.12	-	5
3238	0.15	0.97	0.17	0.022	0.011	Trace	0.62	0.13	-	5
3239	0.16	1.08	0.06	0.022	0.010	Trace	0.69	0.15	0.15	6
3240	0.15	1.13	0.13	0.022	0.010	Trace	0.62	0.13	0.13	6
3241	0.15	0.94	0.09	0.023	0.010	Trace	0.68	0.12	0.17	6

There are rather wide variations in these compositions, but it was decided to proceed with the further examination of the steels. Two ingots from each set of three were forged to plate 4 inches wide by 5/8 inches thick for weldability testing, and the third to 1.1/4 inch diameter bar. These two section sizes are equivalent in that they cool at similar rates (according to B.S. 971, 5/8 inch thick plate is equivalent to 1.23 inch diameter bar, in air cooling). The bar material was prepared from the last ingot in each set, as tabulated in Table II.

b) Heat Treatment of Bar Material

Each 1.1/4" diameter bar was cut into four sections, of which two were designated X and two Y. All the bar material was then heat treated as follows:-

Bars X .... Normalise from 900°C, Temper at 500°C for 1 hour.

Bars Y .... Normalise from 900°C, Temper at 650°C for 1 hour.

The bars were allowed to air cool from the tempering temperature in order to check on the possibility of temper brittleness in the absence of molybdenum.

c) Mechanical Properties of Bar Material

The heat-treated bars were machined to form standard Izod and tensile test pieces, and subjected to test. Hardness measurements were also made. The results are given in Table III.

TABLE III

Mechanical Properties of Six Vanadium-Bearing Steels

(Bars X .... Normalised 900°C, Tempered 500°C/1 hour, air cool.)
(Bars Y .... " 900°C, " 650°C/1 hour, " ")

Mark	Yield Point (0.2% Proof (tons/sq.in.)	Max Stress (tons/sq.in.)	Elongation per cent.	Reduction in area per cent.	Izod Impact: ft. lb.
3209X 3209Y	32.0 30.4	41.6 39.6	28.0 29.0	61.6 64.0	62, 57, 80. 70, 73, 35.
3212X 3212Y	33.6 33.6	44.0 43.2	25.0 24.0	57.2 61.6	44, 70, 40. 57, 66, 73.
3215X 3215Y	34.0 36.4	44.7 44.8	21.0 22.0	50.0 59.6	35, 27, 26. 76, 76, 73.
3231X 3231Y	29.6 29.6	39.6 38.0	30.0 30.0	66.0 72.5	85, 88, 92. 91, 92, 98.
3238X 3238Y	26.0 26.0	35.2 34.0	35.0 35.0	72.5 72.5	96, 94, 92. 95, 97, 96.
3241X 3241Y	27.6 29.2	36.0 36.4	30.0 30.0	66.0 66.0	85, 83, 82. 85, 93, 93.

The B.W.R.A. steels A and B, on which these six vanadium-bearing steels are based, were intended to have an 0.2% Proof stress of not less than 30 t.s.i. in the normalised and tempered condition. The data in Table III show that this strength level is maintained in steel A when vanadium is substituted for molybdenum and even when the vanadium content is reduced to 0.12%. In steel B on the other hand the 0.2% proof stress falls to 29.6 t.s.i. when a direct replacement of vanadium for molybdenum is made, and to 26.0 t.s.i. when a reduced vanadium content is used.

The ductility of all the steels is good in relation to their strength and the Izod impact value at room temperature is also very high, except in specimens 3212X and 3215X. Even in these specimens the Izod toughness is only poor in a comparative sense, and may indicate poor quality steel rather than inherent poor toughness.

In general the specimens tempered at 650°C tended to be better in yield ratio, ductility and toughness than those tempered at 500°C.

d) Heat Treatment and Mechanical Properties of Plate Material

The plate material was all heat treated by normalising at 900°C, and tempering at 650°C for 1 hour, air cooling after tempering. Because of the variations in chemical composition in the experimental steels, it was decided to carry out check mechanical tests on samples cut from the heat treated plates. The results are given in Table IV, together with the cognate data on the bar material repeated from Table III.

TABLE IV

Mechanical Properties of Six Experimental Steels

(5/8" thick plate, normalised 900°C, tempered 650°C/1 hour)
(1.1/4" diam. bar, " " " " ")

Spec.	Cast. No.	Material	0.2% Proof Stress (t.s.i.)	Ultimate Tensile Stress (t.s.i.)	Elongation (per cent)	Reduction of Area (per cent)
1	3207	plate	28.0	37.2	35	72
	3208	"	35.0	43.6	32	70
	3209	bar	30.4	39.6	29	64
2	3210	plate	33.3	41.3	34	70
	3211	"	32.4	43.2	31	70
	3212	bar	33.6	43.2	24.0	61.6
3	3213	plate	42.6	50.6	26	67
	3214	"	45.2	54.0	22	64
	3215	bar	36.4	44.8	22.0	59.6
4	3216	plate	32.1	42.3	31	67
	3230	"	32.4	41.6	29	70
	3231	bar	29.6	38.0	30.0	72.5
5	3232	plate	29.2	38.2	36	72
	3233	"	27.7	35.3	41	75
	3238	bar	26.0	34.0	35.0	72.5
6	3239	plate	35.2	43.8	29	70
	3240	"	34.9	42.0	34	72
	3241	bar	29.2	36.4	30.0	66.0

When due allowance has been made for composition variations, in particular with respect to carbon content, it is clear that the plate material exhibits higher values of proof stress and ultimate tensile stress than the bar material. This could be due to the different forging conditions, since the plate material was subjected to a greater degree of hot work, in flattening out to 4 inch by 5/8 inch section, than was the bar material. However, a further possible cause of variation was in the microstructure produced by heat treatment.

e) Microscopic Examination

Samples of all eighteen experimental steels were taken from the heat treated test specimens after mechanical testing, care being taken to select specimens which had not been cold worked in the testing process. These samples were polished and etched in 2 per cent. Nital and the structures examined under the microscope.

The microstructures were variable, but all showed ferrite as a major constituent. The carbide phase was present either as a fine pearlite or troostite or as tempered martensite; both were present in some cases, in varying proportions. The actual grain size was considerably smaller in the specimens taken from plate than in those taken from bar, confirming the greater degree of hot work in the former. The microstructures are given in Table V together with the carbon content and proof stress of the corresponding test pieces.

TABLE V

Relationships between Microstructure, Carbon Content and 0.2% Proof Stress in Six Experimental Steels

(1.1/4" diam. bar or 5/8" thick plate, normalised 900°C, tempered 650°C/1 hour).

Spec.	Cast No.	Material	Microstructure	Carbon Content	0.2% Proof Stress (t.s.i.)
1	3207	plate	F + P	0.12	28.0
	3208	"	F + P	0.17	35.0
	3209	bar	F + P	0.16	30.4
2	3210	plate	F + P + M	0.15	33.3
	3211	"	F + P + M	0.18	32.4
	3212	bar	F + M	0.19	33.6
3	3213	plate	M + F	0.17	48.6
	3214	"	M + F	0.17	45.2
	3215	bar	F + M + P	0.17	36.4
4	3216	plate	F + M + P	0.20	32.1
	3230	"	F + P + M	0.17	32.4
	3231	bar	F + P	0.16	29.6
5	3232	plate	F + P + M	0.15	29.2
	3233	"	F + P + M	0.13	27.7
	3238	bar	F + P + M	0.15	26.0
6	3239	plate	F + M	0.16	35.2
	3240	"	F + M	0.15	34.9
	3241	bar	F + M + P	0.15	29.2

F:- Ferrite, M:- Tempered Martensite
P:- Pearlite or Troostite.

Typical microstructures are shown in Figs. 1-6, all photographed at 100 magnifications. Fig.1. is typical of plate material, Fig.2. of bar material, both having a ferrite-pearlite structure. The much smaller grain size of the former is apparent. Referring back to Table V, it is clear that this grain size difference must account for the lower proof stress of the bar material, in those cases where the microstructures are the same (specifications 1 and 5).

Fig.3. shows an intermediate microstructure of ferrite plus pearlite and some tempered martensite, and Fig.4. a microstructure in which tempered martensite predominates. In general, where some martensite is formed, the tendency is for the plate material to contain more than the corresponding bar material. This difference may be due to slightly faster cooling rates in the plate than in the bar, but the finer grain size may also have had some influence.

Thus the lower proof stress of the bar material may be explained on these grounds, namely a coarser grain size and a tendency to harden to a smaller degree than the plate material. An anomalous result occurs in Specification 2, in which the bar material hardened more than the corresponding plate. The two microstructures are shown in Fig.5. (plate) and Fig.6. (bar). This anomaly may be due to some accident in the normalising of the bar, but it is significant that although the proof and ultimate stress values for this bar are high, the ductility is comparatively low, as can be seen by reference to Table IV.

3. DISCUSSION

It is perhaps unfortunate that at the section sizes and under the cooling conditions required to produce the materials required for these experiments, the steels should have been on the verge of air hardening. According to the exact circumstances, some have given a hardened structure, others have given a ferrite-pearlite structure, and half have given an intermediate structure. These variations in microstructure have to some extent obscured the significance of the data, since the mechanical properties vary as would be expected from those variations.

The original steels A and B, heat treated under comparable conditions, give 0.2% Proof stress values of 31.2 t.s.i. and 29.7 t.s.i. respectively. If we compare these results with those on the two groups of experimental steels, 1 to 3 and 4 to 6 respectively, the following general conclusions can be drawn:-

a) the replacement of Mo by the same amount of V causes some improvement of mechanical properties in both Steel A and Steel B

b) the replacement of Mo by a reduced amount of V gives equivalent properties in Steel A and lower properties in Steel B.

c) the partial replacement of Mo by V gives an improvement in both Steel A and Steel B.

The effect of microstructure on mechanical properties has already been touched upon. This is highly important, since it has been seen that the steels are on the verge of air hardening. If the cooling rate of the steel were reduced, as it would be if larger section sizes were heat treated, the formation of martensite would suppressed, and the pearlite structure would be coarsened. The undoubted effect of this would be to reduce the mechanical properties of the steel. It is commonly held, particularly in the U.S.A. that the mechanical properties of a hardenable steel are dependent on its carbon content and microstructure, the alloy content only being of importance in so far as it affect the latter. The difference in 0.2% proof stress between Cast Nos. 3208 (35.0 t.s.i.) and 3214 (45.2 t.s.i.) each with 0.17% carbon is very significant. It can be said that the drop in properties will be marked as the microstructure changes from martensitic to pearlitic, and much more gradual as the pearlitic structure becomes coarser. It is to be expected therefore that if these steels are normalised in larger section sizes, the proof stress values will fall.

In the heat affected zone of a weld, on the other hand, the cooling rates will be much higher. This is quite obvious when one considers that in this zone, heat is being lost not only to the surrounding air, as in air cooling, but also to the surrounding cooler metal. Hence the microstructure of the heat affected zone is likely to be largely martensitic, since the steels have been shown to be on the verge of full hardening even when air cooled. Hence the heat affected zone hardness and the weldability of these steels will not necessarily correlate with the mechanical properties. At more rapid cooling rates the steels will in fact develop much higher mechanical properties than are produced by the normalising and tempering treatment considered here.

4. CONCLUSIONS

a) In a normalised and tempered weldable steel containing 0.15%C, 0.9%Mn, 0.6%Ni, 0.9%Cr, and 0.22%Mo, the Mo can be replaced by a smaller amount (about 0.14%) of V with no loss in proof stress.

b) In a normalised and tempered weldable steel containing 0.15%C, 1.1%Mn, 0.2% Max Ni, 0.6%Cr, and 0.22%Mo, the Mo can be replaced by the same amount of V with no loss in proof stress.

c) There is no evidence of temper brittleness in such steels when air cooled from the tempering temperature.

d) When normalised in the form of 1.1/4 inch. diam. bars, or 5/8 inch thick plates, the steels are on the verge of air hardening. Apart from ferrite the microstructures contain sometimes pearlite, sometimes martensite and sometimes both.

e) This variation in microstructure is responsible for variations in the mechanical properties. The proof stress is much higher than the minimum required, when the structure contains much martensite.

Figs. 1-6. Typical Microstructures in Vanadium-Bearing Weldable H.T.Steels.

(Etchant:- 2% Nital)
(Magnification:- x 1000 diameters)

1.1/4in. diam. bar or 5/8in.thick plate, normalised 900°C,
tempered 650°C/1 hour.

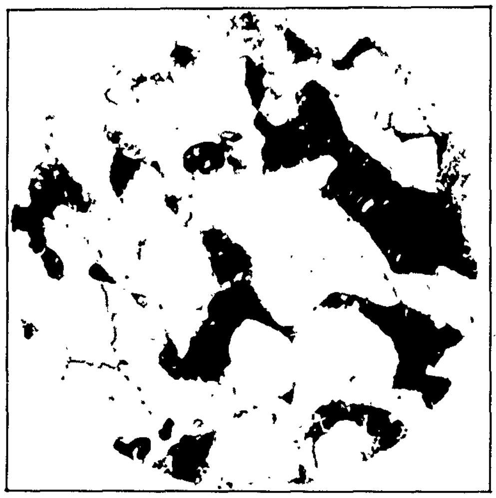

Fig. 1. Cast No.3208
Plate C 0.17%
0.2% Proof 35.0.t.s.i.

Fig. 2. Cast No.3209
Bar C 0.16%
0.2% Proof 30.4 t.s.i.

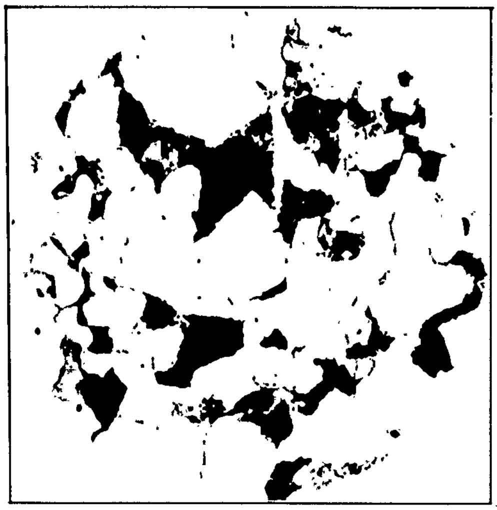

Fig. 3. Cast No.3210
Plate C 0.15%
0.2% Proof 33.3 t.s.i.

Fig. 4. Cast No.3214
Plate C 0.17%
0.2% Proof 45.2 t.s.i.

Fig. 5. Cast No.3211
Plate C 0.18%
0.2% Proof 32.4 t.s.i.

Fig. 6. Cast No.3212
Bar C 0.19%
0.2% Proof 33.6 t.s.i.

PART II

WELDABILITY OF TWELVE LOW-ALLOY STEELS CONTAINING VANADIUM

by

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(British Welding Research Association)

Synopsis

The weldability of twelve low-alloy steels containing vanadium has been investigated. In a previous investigation[1], two low-alloy manganese-nickel-chromium-molybdenum steels were shown to combine good weldability with good mechanical properties. The twelve steels now reported have compositions based on those of these two steels, but have reduced and zero molybdenum contents, and contain vanadium. The steels have been tested for weldability on the B.W.R.A. "Controlled Thermal Severity" test assembly, using mild-steel electrodes with a low-hydrogen type coating.

INTRODUCTION

A series of 35 low-alloy manganese-nickel-chromium-molybdenum steels, made from 18 lb. high-frequency induction-furnace melts, was tested previously[2] for weldability and mechanical properties. Similar tests[1] were then made on two steels, made in two-ton casts, with compositions based on those of steels of the experimental series which gave the best combinations of weldability and mechanical properties. These two steels, referred to as steels A and B, also showed excellent weldability and good mechanical properties.

Following the suggestion by the B.S.A. Group Research Centre that in the interests of molybdenum economy, molybdenum in these steels could be replaced wholly or in part by vanadium, the Research Centre prepared experimental casts of twelve steels six of them being based on the composition of steel A, and six on the composition of steel B. The steels were tested for mechanical properties by the Research Centre and the results have been reported in Part I of this composite report.

Samples of the alloys in the form of $\frac{5}{8}$" plates were supplied to the B.W.R.A. and the weldability of the steels was assessed in terms of the resistance to crack formation in the heat-affected zone adjacent to a restrained weld, under controlled conditions of cooling.

DETERMINATION OF WELDABILITY

1. Test Employed

To assess the weldability of the steels, the B.W.R.A. "Controlled Thermal Severity" (C.T.S.) test was used. This test, which has been described previously[3], makes it possible to simulate the cooling conditions occurring in any type of structural joint.

In the present tests, three grades of cooling severity were chosen, with Thermal Severity Numbers (as defined previously[3]) of 4, 6 and 14*, the last of these representing conditions of cooling as severe as these occurring in most types of structural joint.

These severities were obtained by using $\frac{1}{2}$ in. thick top plates, bolted to $\frac{1}{2}$ in. or $1\frac{1}{2}$ in. bottom plates, one weld with bithermal heat flow and both welds with trithermal flow being used in the tests. Applying the formula for calculating the thermal severity number (T.S.N.), we have:-

* Owing to the great difference in plate thickness, tests with a nominal severity of T.S.N.14 probably had a true severity of about T.S.N.12.

Top plate thickness	Bottom plate thickness	T.S.N. Bithermal weld	T.S.N. Trithermal weld
½ in.	½ in.	4	6
½ in.	1½ in.	-	14

The top plates for the tests were machined from the experimental steels, and the bottom plates were all made from steel A, since there was not sufficient material available from the experimental casts to provide complete C.T.S. assemblies.

Mild-steel electrodes with a low-hydrogen type coating were used for all the tests; these electrodes are especially recommended for the welding of low-alloy steels.

2. Materials Used

The twelve experimental steels were made in 14 lb. high-frequency induction-furnace melts. Each ingot was forged to a plate approximately 15 by 4 by 5/8 in., and these plates were then normalised from 900 deg.C., followed by tempering at 650 deg.C. for 1 hour.

The cast analyses of the twelve steels together with those of steels A and B are given in Table I.

TABLE I

Cast Analyses of Experimental Steels

Steel No.	C%	Si%	S%	P%	Mn%	Ni%	Cr%	V%	Mo%
54	0.12	0.11	0.021	0.012	0.57	0.75	0.87	0.22	-
55	0.17	0.11	0.021	0.010	0.69	0.70	0.90	0.22	-
56	0.15	0.09	0.025	0.010	0.78	0.73	0.92	0.14	-
57	0.18	0.05	0.021	0.010	0.74	0.83	0.88	0.14	-
58	0.16	0.18	0.018	0.010	0.86	0.79	0.97	0.14	0.19
59	0.17	0.20	0.021	0.010	0.99	0.78	0.95	0.14	0.19
60	0.20	0.16	0.025	0.010	1.24	0.10	0.71	0.23	-
61	0.17	0.15	0.021	0.010	1.23	0.10	0.70	0.19	-
62	0.15	0.16	0.022	0.010	1.21	0.14	0.68	0.18	-
63	0.13	0.14	0.024	0.011	1.13	0.12	0.69	0.12	-
64	0.16	0.06	0.022	0.010	1.08	Trace	0.69	0.15	0.15
65	0.15	0.13	0.022	0.010	1.13	Trace	0.62	0.13	0.13
A	0.14	0.18	0.032	0.017	0.89	0.56	0.93	-	0.22
B	0.14	0.30	0.027	0.016	1.14	0.23	0.66	-	0.24

The bottom plates of the test assemblies were all made from the two-ton cast of steel A.

Mild steel, 8 S.W.G. electrodes, B.S.1719 classification E.614 were used for all anchor welds and test welds. All the electrodes used for the test were taken from the same batch, to maintain uniform test conditions.

3. Experimental Procedure

(a) Preparation of plates and electrodes

All the plates were drilled with 9/16 in. diameter holes to accommodate the clamping bolts, and surface-ground on the contact surfaces. The edges of the top plates were machined. The finished top plates were 3 by 3 by $\frac{1}{2}$ in., and the bottom plates were 7 by 4 by $\frac{1}{2}$ in., and 7 by 4 by $1\frac{1}{2}$ in. respectively for the two sizes of assembly.

The electrodes were heated in an air-circulating oven at 110 deg.C. for a minimum of one hour, to ensure that the moisture content (potential hydrogen) in the coatings was kept at a constant low value.

The electrodes were used immediately after removal from the oven.

(b) Testing Procedure

The full procedure for using the C.T.S. test has been described previously[4]. Each anchor weld consisted of three runs in the horizontal position, with a welding current of 180 amp. The assembly was held at an angle of 45 deg. to the horizontal in a heat-insulated jig, so that each test weld was made in the downhand position, and no heat was conducted away from the assembly. Each test weld was made with the assembly initially at room temperature.

The electrodes were marked, so that 4 in. of electrode was used for each 3 in. test weld. All welds were made with alternating current, under approximately the same conditions, the following figures being typical:-

Open-circuit voltage:	105 volts.
Arc voltage:	22 volts.
Welding current:	178 amps.
Time of welding:	26 sec.
Energy input:	28,000 joules per in.

The welding current was measured by means of a moving-iron ammeter and a current transformer, the voltage by a moving-coil voltmeter, and the total energy input by an induction-type integrating watt-hour meter. The energy input used for each test weld is shown in Table II.

(c) Sectioning and Examination of Welds

To allow adequate time for the formation of hard-zone cracks[5], the assemblies were left bolted together for at least three days, and no welds were sectioned until at least a week after welding.

The test welds were sawn out parallel to the welding direction, and sectioned to provide three specimens, one 3/4 in. from the start of the weld, one at the centre, and one 3/4 in. from the end of the weld.

These specimens were polished mechanically, and etched in a solution of 3 per cent picric acid and 3 per cent hydrochloric acid in alcohol. The specimens were examined microscopically for cracks; the crack lengths were measured using a projection microscope, and were expressed as a percentage of the length of the fillet leg in which they occurred.

(d) Hardness Exploration

After polishing and etching, hardness tests were made on the centre section of each test weld, as shown in Fig.1. The tests were made with a diamond-pyramid indenter, using a 10 kg. load. The method of testing, and the terms used in the tables, are as described in previous work[2].

4. Experimental Results

The results of the weldability tests are shown in Table II.

Since only the top plate of each assembly was made from the steel under test, it was only intended to measure crack lengths in the vertical leg of each weld. In the tests, however, no cracks occurred in the horizontal leg of any of the welds. This confirmed the excellent weldability of steel A, as mentioned in the footnote to Table V.

No cracks occurred on any of the welds made with $\frac{1}{2}$ in. bithermal flow (T.S.N.4.) even with steel 59, which had an average plate hardness of 259 D.P.N. and a maximum hardness in the heat-affected zone of 413 D.P.N.

On two of the steels, cracks occurred in specimens welded with both T.S.N.6 and T.S.N.14; on seven of the steels, cracks occurred with T.S.N. 14 only; three of the steels showed complete absence of cracking.

There was a general increase of crack severity with plate hardness, and also with the hardness in the heat-affected zone, but no definite relationship can be established in view of the limited number of results available with each test severity.

TABLE II

Details of Welding Conditions, Fillet Size, Hardness and Cracking

8 S.W.G. Electrodes, Class E.614

Steel No.	T.S.N.	Energy Input ($\times 10^{-3}$ joules/ in.)	Av. Leg Length (in.)	Hardness D.P.N. (10 kg. load)				Av. Cracking V. leg %
				Heat-affected zone		Av. Weld	Av. Plate	
				Max.	Av. Peak			
54	4 6 14	28.6 29.0 28.3	0.24 0.26 0.24	282 311 339	277 297 329	230 224 245	176 174 176	nil nil nil
55	4 6 14	28.9 30.0 27.7	0.25 0.26 0.25	342 377 374	331 368 371	219 247 242	198 198 193	nil nil <1
56	4 6 14	29.3 28.7 27.5	0.24 0.23 0.23	355 367 399	349 356 381	231 230 243	190 183 181	nil nil nil
57	4 6 14	28.2 29.8 27.6	0.24 0.24 0.22	366 402 417	353 394 413	225 239 252	199 199 208	nil nil 4
58	4 6 14	29.3 28.4 26.6	0.25 0.23 0.23	393 411 411	389 405 410	232 230 235	229 230 244	nil nil 47
59	4 6 14	27.7 27.6 27.7	0.24 0.24 0.24	413 427 431	409 421 428	224 245 250	259 265 270	nil 76 71
60	4 6 14	28.2 29.3 28.4	0.23 0.25 0.24	370 427 423	368 405 417	225 247 241	185 187 188	nil 73 23
61	4 6 14	29.3 28.1 27.5	0.24 0.23 0.24	358 377 393	350 369 385	220 230 227	189 188 185	nil nil 2
62	4 6 14	28.9 30.0 28.7	0.25 0.26 0.25	318 358 388	312 355 381	229 233 248	171 166 180	nil nil 33
63	4 6 14	28.3 28.0 28.2	0.25 0.25 0.22	306 317 352	297 316 347	217 222 242	160 158 161	nil nil nil
64	4 6 14	32.3 28.2 27.6	0.28 0.23 0.24	345 401 407	336 397 403	229 239 249	212 210 201	nil nil 76
65	4 6 14	28.2 26.0 27.1	0.25 0.23 0.24	333 361 399	329 355 387	224 231 250	198 189 199	nil nil 28

A photomacrograph of one of the weld sections is shown in Fig.2. The crack has "forked", giving the appearance of two distinct overlapping cracks in the section illustrated.

DISCUSSION

A brief summary of the results of all the tests is given in Table III.

The best combination of weldability and mechanical properties was given by steel 55, which had a yield stress of 35 tons per sq.in.; only very slight cracking occurred on one section of the weld made with T.S.N.14 on this steel.

TABLE III

Summary of Results

Steel No.	Basic Composition	C%	V%	Mo%	Yield Stress or 0.2% proof stress (tons/sq.in.)	* T.S.N.	Hardness D.P.N. Av. peak in heat-affected zone	Hardness D.P.N. Av. plate	Av. Cracking V. leg %
54	Steel A	0.12	0.22	-	28.0	14	329	176	nil
55	"	0.17	0.22	-	35.0	6 14	368 371	198 193	nil <1
56	"	0.15	0.14	-	33.3	14	381	181	nil
57	"	0.18	0.14	-	32.4	6 14	394 413	199 208	nil 4
58	"	0.16	0.14	0.19	42.6	6 14	405 410	230 244	nil 47
59	"	0.17	0.14	0.19	45.2	4 6 14	409 421 428	259 265 270	nil 76 71
60	Steel B	0.20	0.23	-	32.1	4 6 14	368 405 417	185 187 188	nil 73 23
61	"	0.17	0.19	-	32.4	6 14	369 385	188 185	nil 2
62	"	0.15	0.18	-	29.2	6 14	355 381	166 180	nil 33
63	"	0.13	0.12	-	27.7	14	347	161	nil
64	"	0.16	0.15	0.15	35.2	6 14	397 403	210 201	nil 76
65	"	0.15	0.13	0.13	34.9	6 14	355 387	189 199	nil 28
Steel 'A' Steel 'B'		0.14 0.14	- -	0.22 0.24	31.2 29.7	18 (Reeve test)	388 428	188 216	6 + 5 +

* The test results are not all quoted in this table. No cracking occurred on tests conducted with lower Thermal Severity numbers than those listed for each steel. Owing to the great difference in plate thickness, tests with a nominal severity of T.S.N.14 probably had a true severity of about T.S.N.12.

\+ The welding tests on steel A and B were conducted on a Reeve test assembly, using class E.217 electrodes, producing very severe test conditions. With the conditions under which steels 54-65 were welded, no cracking would be expected on steels A and B.

Steel 56, with a similar composition, gave a slightly lower yield stress with complete absence of cracking. These two steels were both based on steel A; they have higher mechanical properties than steel A, but the tests indicate that they have slightly inferior weldability. The excellent weldability of steel A was confirmed by the fact that though the bottom plate of each C.T.S. assembly was made from steel A, no cracks were found in the horizontal leg of any of the test welds.

Steel 58 was also interesting, in that it had a yield stress (or 0.2 per cent proof stress) of 42.6 tons per sq.in., and yet did not crack on the ½ in. trithermal assembly (T.S.N.6.)

It would appear that the molybdenum content of steel A, 0.22 per cent, could be replaced by about 0.15 per cent vanadium, producing a steel with a yield stress in the region of 34 tons per sq.in. in the normalised and tempered conditions, with good weldability when using electrodes with a low-hydrogen type coating.

CONCLUSIONS

1. The replacement of molybdenum by vanadium in a low-alloy steel such as steel A improves the mechanical properties of the steel in the normalised and tempered condition without unduly affecting the good weldability when using low-hydrogen electrodes.

2. The steel which gave the best combination of weldability and mechanical properties was one containing approximately 0.17% carbon, 0.7% manganese, 0.7% nickel, 0.9% chromium, and 0.22% vanadium, with a yield stress of 35 tons per sq.in. in the normalised and tempered condition when heat treated in the form of ½ in. thick plate.

Acknowledgments

The valuable discussion on the work, given by members of the High Tensile Weldable Structural Steel Investigation Steering Committee of the Ministry of Supply, is gratefully acknowledged.

Thanks are also due to the B.S.A. Group Research Centre for supplying the experimental steels, for the chemical analyses, and for mechanical test results on the steels.

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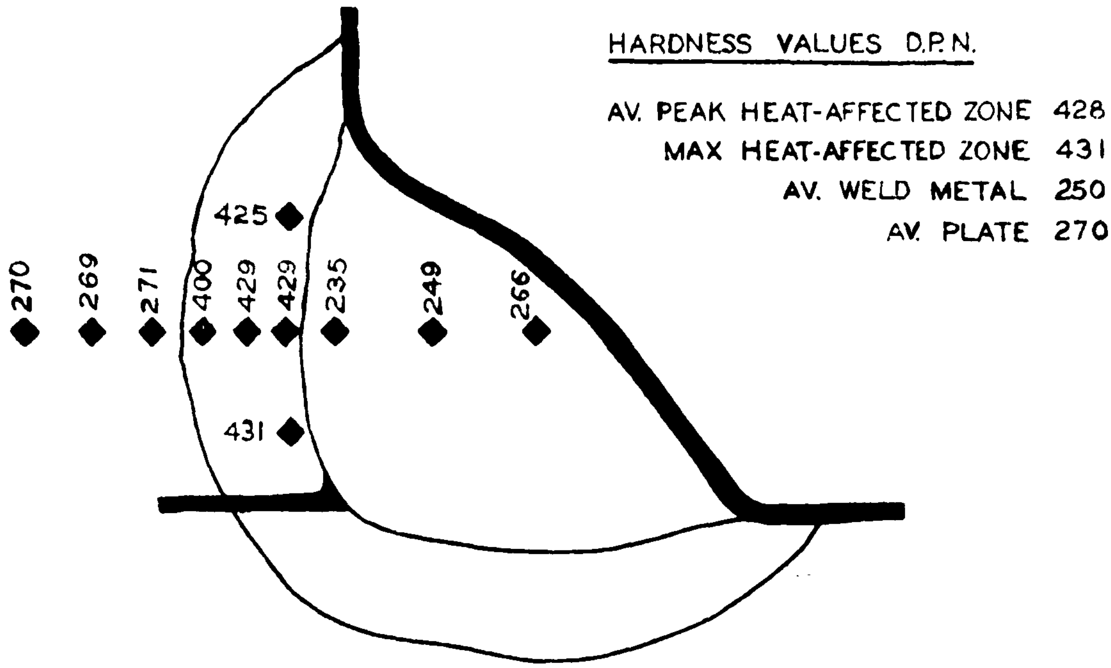

FIG. 1. DIAGRAM INDICATING POSITIONS OF HARDNESS IMPRESSIONS. VALUES GIVEN ARE FOR STEEL 59, T.S.N. 14.

FIG. 2. CRACK IN HEAT-AFFECTED ZONE. STEEL 64, T.S.N. 14.

PART III

THE EFFECT OF MOLYBDENUM AND VANADIUM ON THE MECHANICAL PROPERTIES OF CERTAIN ALLOY STEELS

by

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SYNOPSIS

Tensile and Izod tests have been made on a number of low-alloy manganese-nickel-chromium steels based on two compositions. Some of the steels contained molybdenum, some contained vanadium and the remainder contained both molybdenum and vanadium.

The substitution of molybdenum by less vanadium gave a lower transition temperature combined with much higher values of 0.02 per cent proof stress, without adversely affecting the weldability of the steels.

The results apply to plates normalised under conditions equivalent to $1\frac{1}{2}$ in. thick sections. It is also shown by reference to earlier work that similar improved properties could probably be obtained with molybdenum steels by tempering at 600°C.

1. INTRODUCTION

As a part of the investigation into the development of higher strength weldable steels, a series of 35 experimental low-alloy manganese-nickel-chromium-molybdenum steels was examined[1] for weldability and mechanical properties. As a result of this work two steels were manufactured in two-ton casts, and weldability and mechanical tests were made on both steels[2]. These two steels were designated A and B.

In order to provide alternative steels economising in molybdenum, the Ministry of Supply accepted an offer from the B.S.A. Group Research Centre to make twelve more experimental steels based on the compositions of Steels A and B, but with the molybdenum either partly or completely replaced by vanadium. These steels were tested[3] for mechanical properties and weldability after heat treatment in the form of $\frac{1}{2}$ - $\frac{5}{8}$ in. thick plate, as described in Part I and II of this composite report.

The weldability and mechanical test results for the experimental vanadium steels were good. Since the test results related to rather thin plate, it was decided, following a suggestion by Dr. L. Reeve, (Chairman of the B.W.R.A. FM.8 Committee) to make further mechanical tests on the steels normalised under conditions equivalent to those occurring in thick plate.

2. MATERIALS

The cast analyses of the twelve vanadium steels are given in Table I and analyses of Steels A and B are also included.

TABLE I

Cast Analyses of Experiment Steels

Steels No.	C%	Si%	S%	P%	Mn%	Ni%	Cr%	V%	Mo%
54	0.12	0.11	0.021	0.012	0.57	0.75	0.87	0.22	-
55	0.17	0.11	0.021	0.010	0.69	0.70	0.90	0.22	-
56	0.15	0.09	0.025	0.010	0.78	0.73	0.92	0.14	-
57	0.18	0.05	0.021	0.010	0.74	0.83	0.88	0.14	-
58	0.16	0.18	0.018	0.010	0.86	0.79	0.97	0.14	0.19
59	0.17	0.20	0.021	0.010	0.99	0.78	0.95	0.14	0.19
60	0.20	0.16	0.025	0.010	1.24	0.10	0.71	0.23	-
61	0.17	0.15	0.021	0.010	1.23	0.10	0.70	0.19	-
62	0.15	0.16	0.022	0.010	1.21	0.14	0.68	0.18	-
63	0.13	0.14	0.024	0.011	1.13	0.12	0.69	0.12	-
64	0.16	0.06	0.022	0.010	1.08	Trace	0.69	0.15	0.15
65	0.15	0.13	0.022	0.010	1.13	Trace	0.62	0.13	0.13
A	0.14	0.18	0.032	0.017	0.89	0.56	0.93	-	0.22
B	0.14	0.30	0.027	0.016	1.14	0.23	0.66	-	0.24

3. EXPERIMENTAL PROCEDURE

In order to simulate, in the experimental steels, the cooling conditions which occur in $1\frac{1}{2}$ in. thick steel a sandwich technique was used. For the tensile tests, where one specimen was required from each steel, the steels were normalised in the form of $\frac{1}{2}$ by $\frac{1}{2}$ by 5 in. bars clamped between $\frac{1}{2}$ in. thick mild steel plates, the contact faces between the bars and plates being machined where necessary to ensure good thermal contact. For the notched-bar impact tests, where a number of specimens were required from each of steels 55, 58 and A, $\frac{1}{2}$ in. thick plates were used in place of the $\frac{1}{2}$ in. square bars.

The sandwiches were normalised by heating at 900°C for $1\frac{1}{2}$ hr. followed by cooling in still air.

The $\frac{1}{2}$ in.sq. bars were machined to give tensile test pieces having a cross-sectional area of 1/20 sq.in. and a parallel length of $2\frac{1}{2}$ in. Stress/strain curves were obtained for each specimen using a Lindley extensometer working on a 2 in. gauge length.

The $\frac{1}{2}$ in. thick plates were each machine to give four standard three-notch 10 mm. sq. Izod test bars. Each steel was tested at 20, 0, -20 and -40°C. using a 120 ft. lb. capacity Izod machine. The temperature of each specimen was measured by means of a clip-on thermocouple of copper and constantan wires with the specimen as the junction. This method gave a temperature variation throughout the cross-section at the notch, of not greater than ± 1 Centigrade degree from the measured temperature. The low test temperatures were obtained by immersing the machine grips and the specimens, immediately prior to test, in absolute alcohol containing solid carbon dioxide.

The check whether the plain vanadium steels were subject to temper brittleness, a $\frac{1}{2}$ in. sq. section bar of steel 55 was heated for 1 hr. at 600°C. and then furnace cooled. A standard three-notch Izod test piece was machined from the bar, and tested on the Izod machine.

4. RESULTS

The tensile test results are given in full in Table II.

There was a marked difference in the type of stress/strain curve, depending upon the presence or absence of molybdenum in the steel. The molybdenum-free steels (54-57 and 60-63) exhibited a definite yield point, whereas those steels containing molybdenum (58, 59, 64, 65, A and B) gave a non-ferrous type of stress/strain curve. Stress/strain relationships for certain steels based on compositions A and B are shown in Figs. 1 and 2, the stress/strain curves being typical of those produced for the various steels. A comparison of curves for steels 56 and 58 (shown in Fig.1) indicates how the addition of molybdenum has markedly affected the form of the stress/strain relationship.

In general the plain vanadium steels gave slightly lower ultimate tensile strengths than the plain molybdenum steels with the same total alloy content. It was difficult to compare these values with those obtained for the steels containing both molybdenum and vanadium, since the total alloy content of these steels was higher. The indications are that the molybdenum-vanadium steels would have the same ultimate tensile strengths as comparable plain molybdenum steels, The ductilities of the steels were nearly always lower where the ultimate strengths were higher.

TABLE II

Mechanical Properties of Steels

Steel No.	COMPOSITION *			Weldability Index	Proof Stress (tons/sq.in.)			U.T.S. (tons/sq.in.)	Elongation on $4\sqrt{A}$ (%)	Reduction in Area (%)
	C%	V%	Mo%		0.02%	0.3%	0.5%			
54	0.12	0.22	-	6A	24.4	yield		34.0	39	72
55	0.17	0.22	-	6B	27.6	yield		37.8	38	70
56	0.15	0.14	-	6A	26.4	yield		37.6	36	72
57	0.18	0.14	-	6B	27.8	yield		39.2	36	68
58	0.16	0.14	0.19	6C	12.5	26.2	29.6	48.6	26	48
59	0.17	0.14	0.19	6D	15.2	30.4	34.2	53.0	26	52
A	0.14	-	0.22	6A	13.0	20.5	22.6	37.6	35	63
60	0.20	0.23	-	6D	30.2	yield		40.6	36	67
61	0.17	0.19	-	6B	27.0	yield		39.0	31	68
62	0.15	0.18	-	6C	26.1	yield		37.1	40	71
63	0.13	0.12	-	6A	24.6	yield		34.3	38	75
64	0.16	0.15	0.15	6C	11.7	22.6	25.4	43.6	28	55
65	0.15	0.13	0.13	6C	12.2	22.0	24.6	42.1	29	57
B	0.14	-	0.24	6A	11.8	21.0	23.2	40.0	35	59

* Steels 54-59 and steel A contained 0.57-0.99% Mn, 0.56-0.83% Ni, and 0.70-0.93% Cr.
Steels 60-65 and Steel B contained 1.08-1.24% Mn, 0.23% max. Ni, and 0.62-0.71% Cr.

The ratio $\frac{\text{0.5 per cent proof stress (or yield stress)}}{\text{ultimate tensile stress}}$ changes with the presence or absence of molybdenum in the steel. For the molybdenum-free steels the ratio varies between 0.69 and 0.74, the average for eight steels being 0.71. For the steels containing molybdenum the ratio is lower (0.53-0.65, average 0.60).

With the ratio $\frac{\text{0.02 per cent proof stress}}{\text{ultimate tensile stress}}$, however the presence of molybdenum in the steel is accompanied by a reduction in value to less than half. The ratio for the molybdenum-free steels is the same as that given for the 0.5 per cent proof stress, due to the presence of a definite yield point; (0.69-0.74, average 0.71). For the steels containing molybdenum however, the ratio is only 0.26-0.35, the average being 0.30.

The results of Izod tests made on steels 55, 58 and A, all based on composition A are given in Fig.3. These results show that the plain vanadium steel gave the lowest transition temperature as measured by both energy and ductility criteria. The steel containing molybdenum and vanadium gave a higher transition temperature and the plain molybdenum steel gave the highest transition temperature. The temperatures for 50 per cent shear fracture were -12°C., 17 C. and over 20°C. for the plain vanadium, molybdenum-vanadium and plain molybdenum steels respectively. Taking 15 ft. lb. energy to fracture as a criterion of notch toughness the same three steels gave temperatures of under -40°C., -35°C., and 2°C. respectively. In addition to having the lowest transition temperature, the plain vanadium steel absorbed a minimum energy of 29 ft. lb. in the lower-shelf region of the transition curve. This value is much greater than the minimum energy of 7 ft. lb. observed for the plain molybdenum steel.

The values obtained from Izod tests on the plain vanadium steel 55, after tempering at 600°C. followed by furnace cooling, were as follows:-

Energy absorbed: 48; 57; 60 ft. lb.

These values indicate that the plain vanadium steels are not unduly susceptible to temper brittleness.

In a previous report[1] a low elastic limit in manganese-nickel-chromium steel was shown to be related to the presence of an unresolved constituent in the steel microstructure. For this reason the microstructure of steel A (molybdenum containing) and steel 55 (molybdenum free) were examined. Photomicrographs of the structures of these two steels in the normalised condition are given in Figs. 4 and 5. Fig.4 shows the structure of steel A which contains an appreciable amount of the unresolved constituent, whereas the molybdenum-free steel 55 (Fig.5) does not contaim the constituent.

Microhardness tests were made on the unresolved constituent using a diamond pyramid indenter with a 1 gm. load. The values obtained, after correcting for error due to the low applied load, were as follows:-

Matric of alloy ferrite.................... 160 D.P.N.

Unresolved constituent .... 410 D.P.N.

The value obtained is consistent with that obtained from a low-carbon (0.14 per cent) martensite or lower bainite structure. The average macrohardness of the structure using a 10kg. load was 183 D.P.N.

5. DISCUSSION

In a previous report[3] it was shown that replacing molybdenum by vanadium in alloy steels A and B gave improved mechanical properties in ½ in. thick section, without adversely affecting weldability.

The mechanical properties observed in this report relate to the same alloy steels normalised in the form of 1½ in. thick section. The results, which are given in Table II, indicate that the highest value of 0.5 per cent proof stress combined with class A weldability[7] is obtained with the plain vanadium steels, although the properties are not much better than those of the plain molybdenum steels. The steels containing both molybdenum and vanadium, with a higher total alloy content, gave the highest values of 0.5 per cent proof stress but only class C weldability.

In some practical applications the 0.02 per cent proof stress is used to assess the merit of the steel. If this criterion is used, the plain vanadium steels show a marked improvement over the other types of steel. The 0.02 per cent proof stress is increased from about 12 tons per sq.in. to about 24 tons per sq.in., i.e. doubled, by substituting 0.24 per cent. Mo by 0.12 per cent V in composition B (see Fig.2). This improvement is achieved with less alloy addition and the weldability of the steel is not reduced from class A. A similar improvement is observed with composition A, as shown in Fig.1.

In other practical applications for arc-welded low-alloy steel low transition temperatures are required. Again the plain vanadium steel examined shows a marked superiority over the steels containing molybdenum, the temperature for 50 per cent shear fracture in the plain vanadium steel being lower by 30-40 Centigrade degrees.

The Izod transition curve for the plain molybdenum steel A shows satisfactory agreement with results obtained from Charpy V-notch tests carried out on this steel by Colvilles Ltd.[5] A comparison of the two sets of results is given in Table III which also shows that the normalising conditions used here gave a good indication of the properties to be obtained from as-rolled $1\frac{1}{2}$ in. thick plate. It is likely that the plain molybdenum steel A would have shown much better notch toughness at room temperature if it had been tempered, since Smith and Whitman[4] have shown that tempering a low-carbon manganese-molybdenum steel more than doubles the energy required to fracture an Izod specimen at room temperature. For this reason it is possible that tempering will also lower the transition temperature of the plain molybdenum steel.

TABLE III

Comparison of Izod and Charpy V-Notch Tests on Steel A

Test	Material Condition	ENERGY ABSORBED (ft. lb.)			Temperature for 50 per cent shear fracture (°C.)
		at -20°C.	at 0°C.	at 20°C.	
CHARPY	As-rolled $1\frac{1}{2}$ in. thick plate.	5	11	27	40
IZOD	Normalised plate eq. to $1\frac{1}{2}$ in. thickness	10	15	20	over 20

The lower transition temperature exhibited by the plain vanadium steel 55 is interesting and shows some agreement with the work of Rinebolt and Harris[6]. These investigators examined the effect of separate additions of vanadium and molybdenum to a steel of basic composition 0.3 per cent C, 1.0 per cent Mn. These results showed that, whereas increasing the molybdenum content raised the transition temperature, increasing the vanadium content raised and then lowered this temperature. The lowering of the transition temperature was observed with a vanadium content of 0.21 per cent, which corresponds closely to that of steel 55 (0.22 per cent V).

It is not possible to compare directly the results obtained here with those of Rinebolt and Harris because of the difference in basic composition of the steels and other variables. However, it is apparent that the improvement obtained in steel A by substituting molybdenum by vanadium is much greater than that obtained in the 0.3 per cent C, 1.0 per cent Mn steel.

This difference may be caused by some effect of alloying elements in composition A (Mn, Cr, Ni and Mo) acting in combination in a way different from their separate effects, or it may be due to the variation in carbon content, e.g. the adverse effects of C and Mo may not be additive when the carbon content is as high as 0.3 per cent in the steel mentioned above[6]. It should also be rembered that the two series of tests being compared were made on Izod and Charpy machines respectively and using material in different conditions of heat treatment.

The results given here which refer to normalised steel, may apply for as-rolled material, but it should be remembered that high values of 0.02 per cent proof stress can be obtained[1,4] by tempering certain molybdenum steels at 600°C. Also the high values of notch toughness for the plain vanadium steel may be due in part to the grain refinement produced by normalising, since Mackenzie and Pow[8] have shown that the notch toughness of vanadium steel is impaired by normalising from higher temperatures. Therefore, the main advantage to be gained by substituting molybdenum by vanadium is the attainment of a high 0.02 per cent proof stress without recourse to tempering, this being achieved with little more than half the alloy addition.

The absence of the unresolved constituent in the steel which gave a definite yield point confirms the results reported earlier[1]. It now appears that the element molybdenum in the steels examined is responsible for the presence of this constituent at the cooling rates involved (normalised $1\frac{1}{2}$ in. thick material. This effect of molybdenum is probably due to its making the transformation of austenite more sluggish, a fact which is well known.

The atomic volume of the molybdenum is much larger than that of the other alloying elements found in steel, e.g. Mn, Ni, Cr, Cu, V. This fact may account in part for the marked effect of molybdenum in retarding the transformation of austenite at low cooling rates.

6. CONCLUSIONS

It has been shown that replacing the whole molybdenum content with a lower vanadium content in certain experimental low-alloy steels gives improved machanical properties and does not result in temper brittleness.

The improvements comprise a much lower Izod transition temperature and the production of a definite yield point with consequent high value of 0.02 per cent proof stress, these improvements being obtained without reducing the weldability of the steels.

The mechanical tests were restricted to plates normalised under conditions equivalent to those obtained in $1\frac{1}{2}$ in. thick section and evidence is given to show that some of the results may apply for similar as-rolled material. It is possible however, that as-rolled vanadium steel may need to be normalised to obtain a more refined structure with consequence good notch toughness.

It has been shown by reference to earlier work[1,4] that most of the improvement gained by the substitution of molybdenum or vanadium should be obtained by tempering the plain molybdenum steel at 600°C.

The presence of a definite yield point has again[1] been shown to be related to the absence of an unresolved constituent in the steel micro-structure. This constituent has the hardness associated with a low-carbon martensite or lower bainite.

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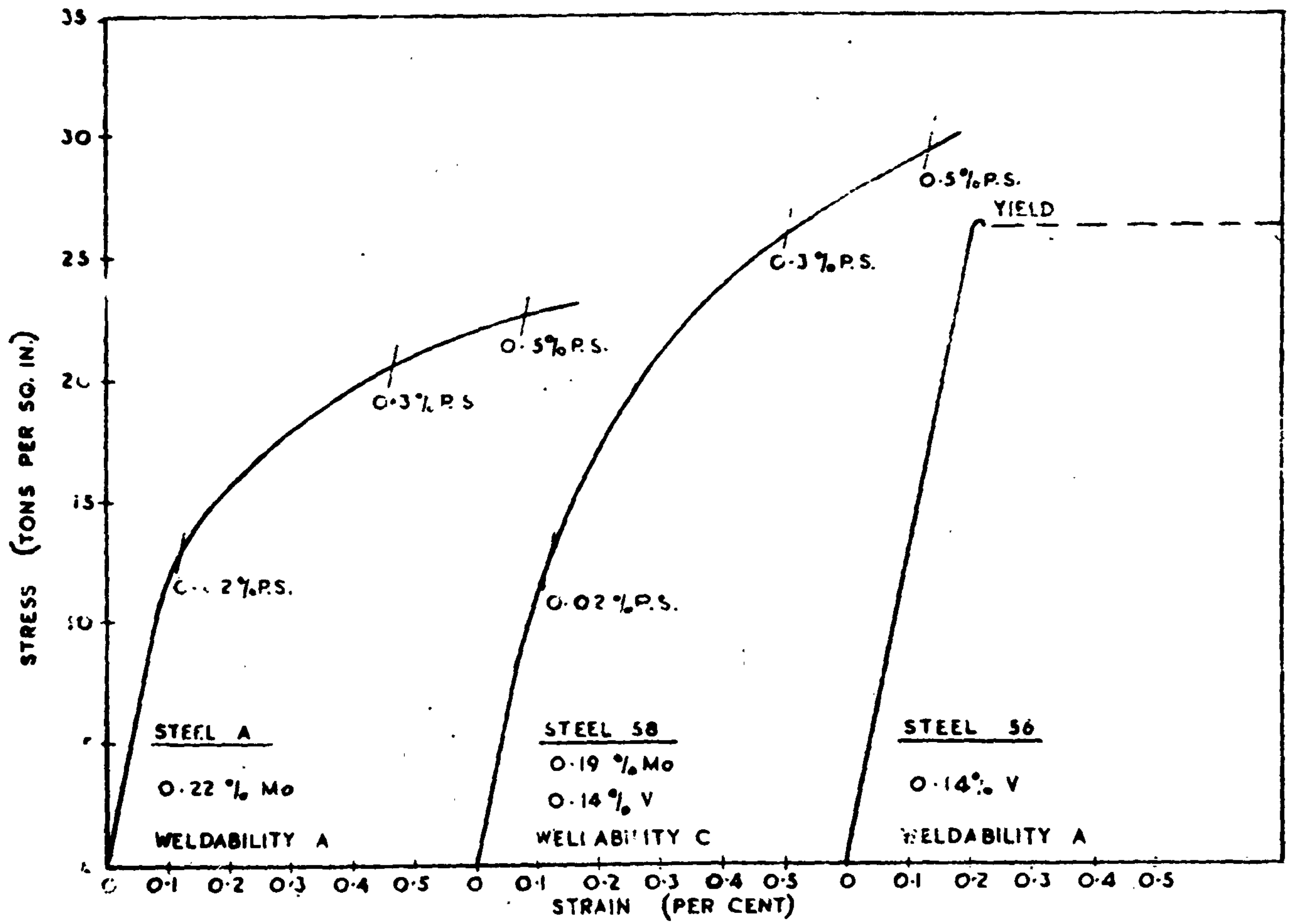

FIG. 1 STRESS/STRAIN RELATIONSHIPS FOR STEELS BASED ON COMPOSITION A

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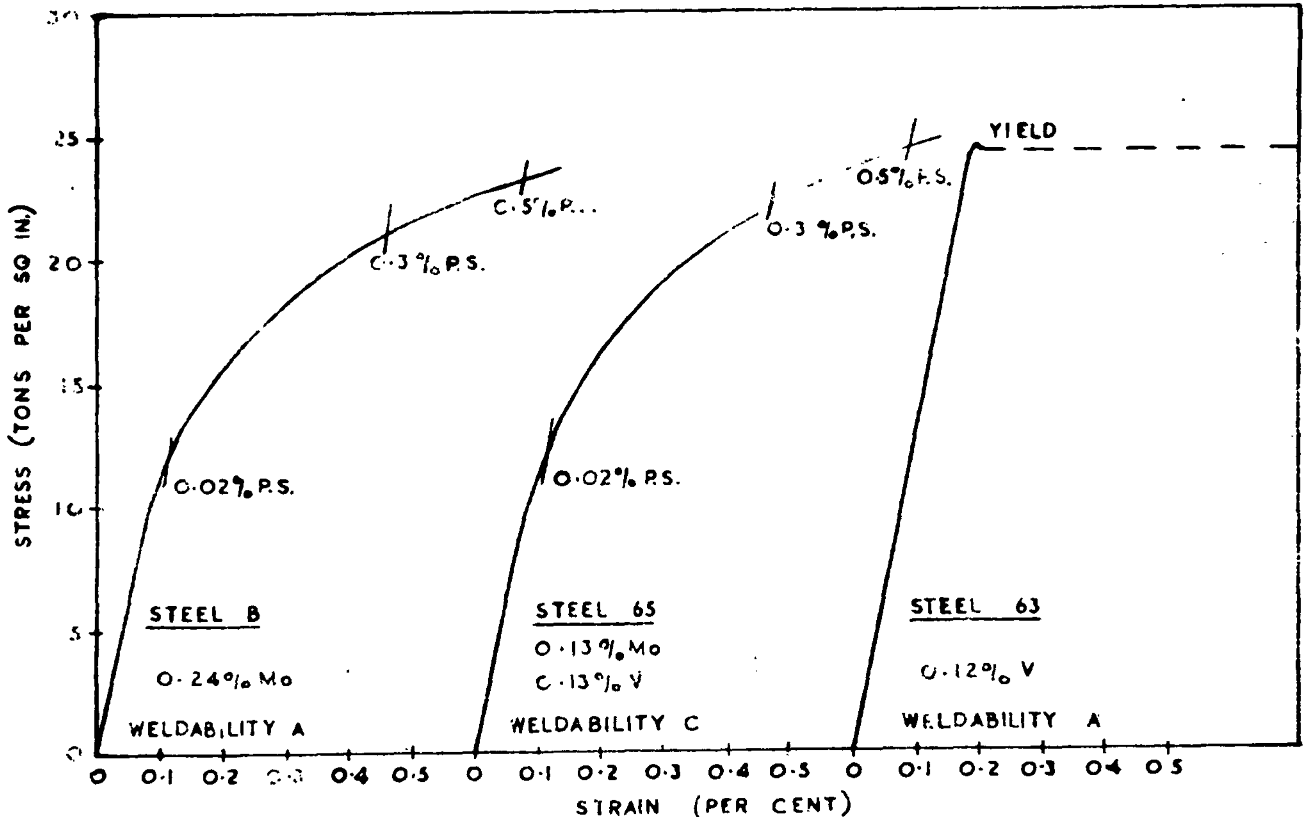

FIG. 2 STRESS/STRAIN RELATIONSHIPS FOR STEELS BASED ON COMPOSITION B

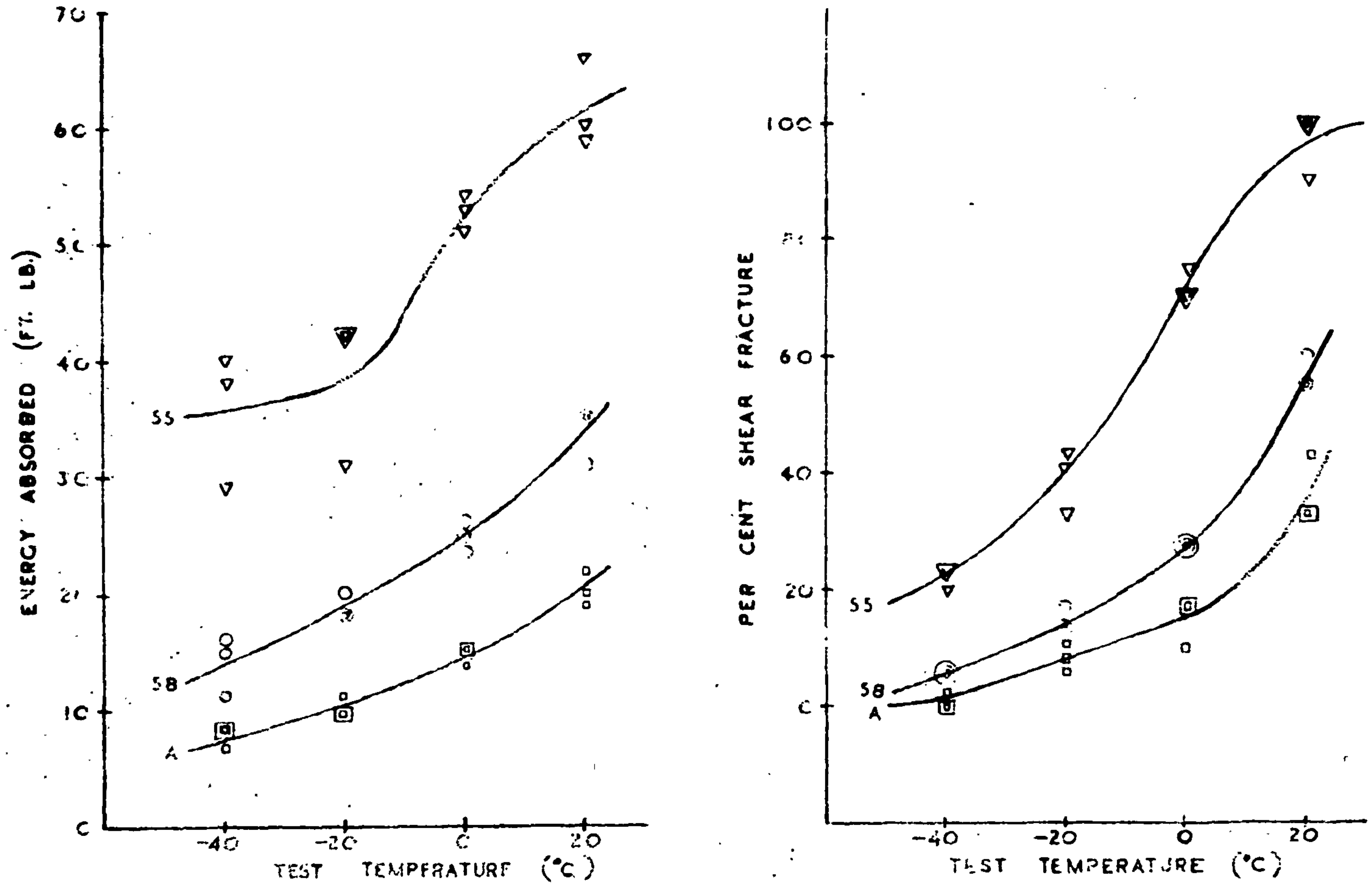

FIG. 3. IZOD TRANSITION CURVES FOR STEELS BASED ON COMPOSITION A

(STEEL COMPOSITIONS: A – 0.22 % Mo; 58 – 0.19 % Mo, 0.14 % V; 55 – 0.22 % V)

Fig.4 Structure containing unresolved constituent. Molybdenum-containing steel A.

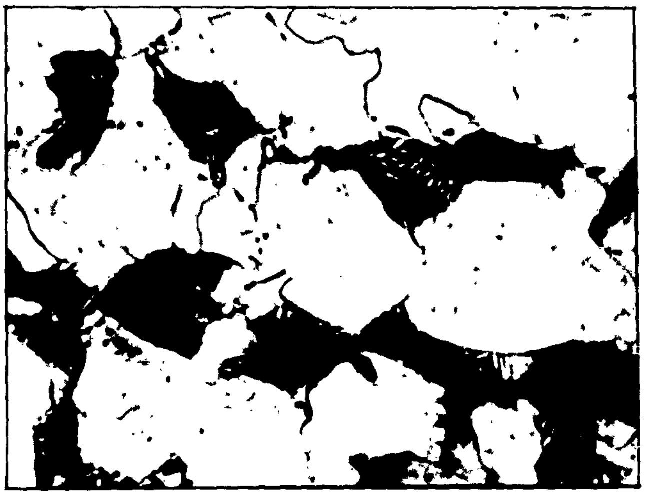

Fig.5 Structure without unresolved constituent. Molybdenum-free steel 55.

Photomicrographs x 2000. Specimens etched in 2 per cent nital.

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